Design of a 20-Ton Capacity Finfish Aquaculture Feeding Buoy

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Abstract*- A design for a 20-ton capacity buoy was developed to feed fish in four submerged cages at an exposed site south of the Isles of Shoals, New Hampshire, USA. The buoy was designed to contain all the equipment necessary to accomplish the feed dispensing tasks as well as have the strength and stability to remain on location in a variety of sea states. New feed handling and distribution systems were developed and tested. To evaluate seakeeping response a Froude scaled physical model was constructed and tested at the Ocean Engineering wave/tow tank at the University of New Hampshire (UNH). The mooring system was designed using the UNH developed finite element analysis program called Aqua-FE. The prototype buoy is now under construction, and is scheduled for deployment in late summer 2006.

I. INTRODUCTION

A prototype finfish aquaculture feed buoy, with a 20-ton feed capacity, was developed to supply feed to four submerged net-pens at an exposed site south of the Isles of Shoals, New Hampshire, USA. This type of feeding system was needed because a commercial system is not available in the United States for exposed sites using submerged cages.

The University of New Hampshire (UNH) has operated an open ocean aquaculture (OOA) site in 52 meters of water approximately 10 km from the New Hampshire coast, in the United States water since 1999. The site is permitted to perform research related to the operational, engineering, biological, and environmental aspects of open ocean aquaculture. For over four years, the site and associated systems have been the focus of an intense engineering and operational analysis program [1], [2], and [3]. From the engineering perspective, studies were conducted to investigate the dynamics so that numerical and physical modeling techniques could be developed to cost-effectively engineer and specify equipment suitable for deployment [4], [5], [6], and [7].

Two prototype feed buoys have been developed previously at UNH, a quarter-ton [8] and one-ton feed capacity buoys. Both of these buoys were designed to feed one submerged cage using water as the medium to transport feed.

The design goal for the 20-ton buoy was to create a system that could operate independently at the OOA site for lengths of time. The buoy must contain all power generation, feeding systems, and electronic equipment required for normal operation. It must also have the hydrodynamic stability to survive the storm conditions normally observed at the exposed OOA site. The buoy feeding system was to be designed to enable four different types of feed to be stored and for each type of feed to supply any of the four cages to which the system is attached. Feed was to be transported, in a water medium, to the cages using submerged feed hoses.

With the design criteria established for the buoy and the buoy feeding system, a general layout for the buoy hull, internal components, and ballast configuration was determined. New systems needed for this size of feed buoy were identified and designed. Physical testing of new systems and their individual components were performed. A Froude scaled physical model was constructed and tested in the UNH ocean engineering wave/tow tank. Mooring system design and components were iteratively determined using a finite element analysis model. Construction has begun, and deployment is scheduled for late summer of 2006.

II. BUOY PHYSICAL DESCRIPTION

The steel buoy hull is 28.2 feet tall, has a diameter of 22.5 feet, has a load draft of 13 feet, and weighs 84 tons fully loaded with feed and fuel (Fig. 1). The uppermost section of the buoy is the machinery house, a 10 foot by 10 foot square that is 7 feet tall. The house contains the majority of the electrical equipment as well as the generator for the buoy. The main hull section of the buoy is below the machinery house and consists of a 22.5 foot diameter cylinder that is almost 10 feet tall. The main hull section contains the bulk of the feed storage silos, diesel fuel tanks, and components of the internal and external feed transport systems. Below the cylinder is a conical section that tapers to a diameter of approximately 16.5 feet over a height of around 5 feet. The lowest section of the buoy is the ballast can. This section is a cylinder of 8.5 feet diameter with a height of 6 feet. Concrete ballast weighing

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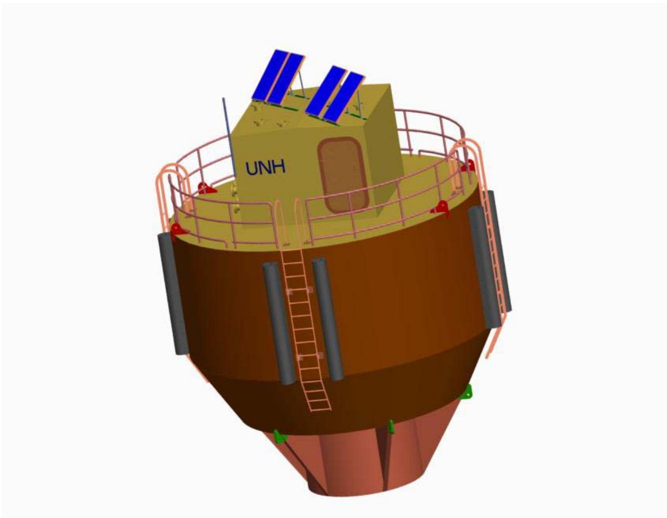

Figure 1. External view of completed 20-ton buoy design.

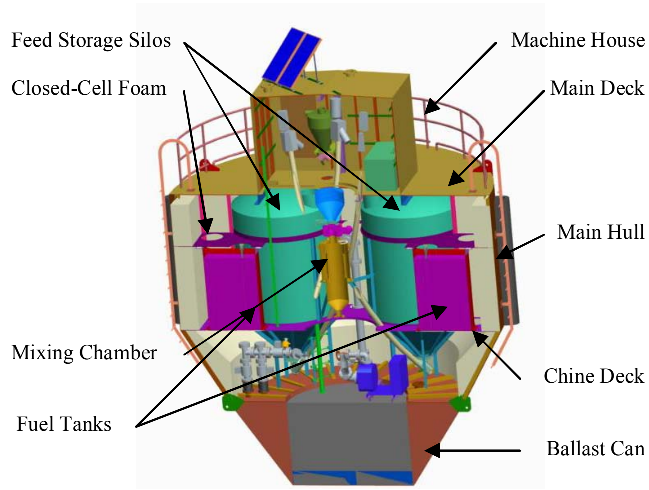

Figure 2. Completed 20-ton buoy design sowing cross-section to view major internal components.

24.4 tons fills this lowest section. Fig. 2 shows a cross-section of the completed design showing major internal components.

Since the buoy is to feed submerged cages from one of four silos placed low around the periphery of the main hull, new internal and external feed transport systems needed to be developed. Mechanical and electrical systems are monitored and controlled by a computer as described in companion papers [9], [10].

Due to the severe sea states that are regularly experienced at the open ocean aquaculture site, survivability of the buoy was of major concern. A major design area that was focused on was the hull structure and ballast to ensure strength and stability of the buoy. Sufficient reserve freeboard and stability to resist ice loads were incorporated into the design. Foam flotation was also included into the design to allow positive buoyancy of the buoy in case of free flooding.

A. Internal Feed Transport System

Since the 20 tons of feed needed to be stored low to aid in stability, an additional major system to handle the feed transfer inside the buoy was added. The main component of the internal feed transport system is a mechanical flex-auger (Fig. 3). The internal feed transfer system begins with feed stored in the storage silos. A mechanical flex-auger is located beneath each feed storage silo (4 total) and is capable of transferring feed pellets through a flexible pipe up to the central collection hopper in the superstructure. All four feed storage silos are able to fill the central collection hopper. Therefore, any storage silo will be able to feed any cage. Once the feed is in the collection hopper, the external feed transfer system moves the feed to the cages.

B. External Feed Transport System

Since the UNH aquaculture site uses submerged cages, the feed must be delivered in a water medium. Due to the size of the proposed buoy design it will have to be moored separately from the existing UNH aquaculture grid [6], resulting in long feed hoses (up to 1000 feet) connecting the buoy to the cages. To protect the hoses they need to be submerged over their full length. Based on these design specifications, it was decided to use a water mixture to deliver the feed (compressed air is often used at many near shore, surface fish farms).

A continuous feeding system was desired to minimize startup time for feeding multiple cages. For a continuous system to function, a free surface (air-water interface) is needed to accept the supply of feed pellets. Pumping water through a pipe creates back-pressure (head) and causes the water level of free surfaces to rise. The continuous feeding system needs to have a method to control the level of the water to eliminate the possibility of flooding the buoy.

The three major components of the external feeding system are the two pumps (supply and feed pump) and the mixing chamber. A schematic of the external feeding system is shown in Fig. 4. A centrifugal pump supplies water at the desired rate

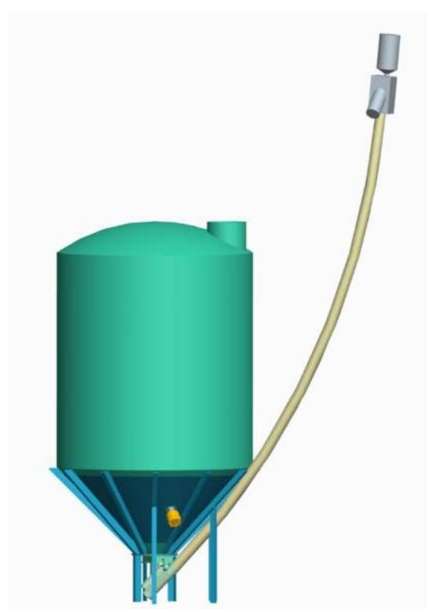

Figure 3. Internal Feed Transport System using mechanical flex-auger. Silo base connected to inlet of flex-auger with discharge at top of flex-auger (collection hopper not shown). One of four total systems shown.

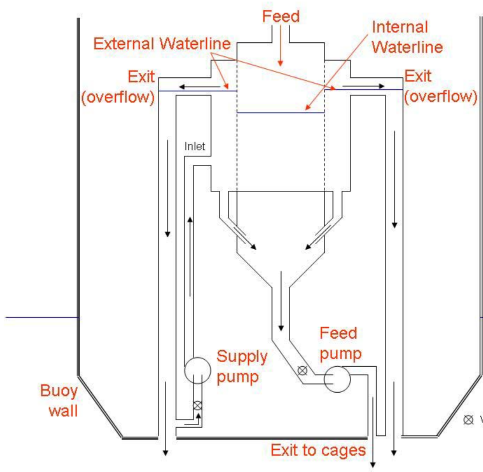

Figure 4. Schematic drawing of external feeding system.

into the chamber. Feed is then dropped into the chamber to form a mixture. The feed pump delivers the mixture to the cages. The feed pump must handle feed passing through the pump with minimal damage to the pellets.

Prior to feeding, electronically activated valves downstream of the feed pump open/close to direct the flow of water to the appropriate discharge pipe to feed the desired cage. The supply pump turns on to allow water to fill the mixing chamber. Once the water reaches the equilibrium level, any extra water will exit through the two exit (overflow) pipes. These pipes are very (~6 inches) in relation to the inlet pipe (~3 inches). The flow rate for the inlet pump is to be a minimum of twice the feed pump so that the mixing chamber will always have water in it. Once the water reaches the desired level, the feed pump will be activated. After the water is moving and the free surface that is needed in the mixing chamber is present, the feed can be introduced. A rotary airlock will control the feed introduction into the mixing chamber.

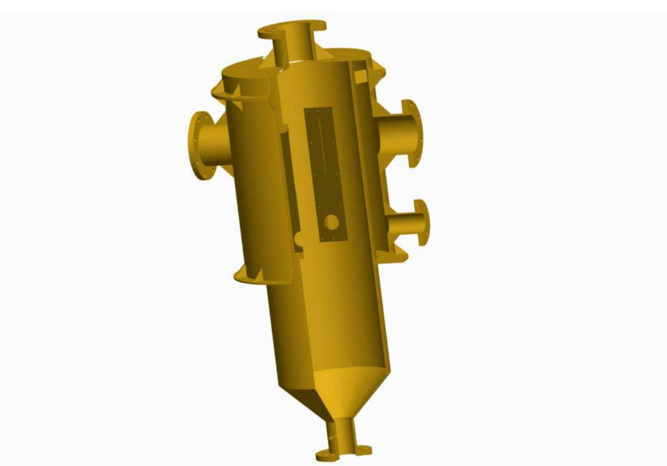

Figure 5. External view of mixing chamber with cut-out showing internal design features.

Mixing Chamber

The mixing chamber, shown in Fig. 5, is a major component of the external feed transfer system. This is where fish feed pellets are introduced into water and pumped to the submerged net pens. The mixing chamber design consists of a large diameter (approximately 24 inches) tank with a smaller diameter tank (approximately 18 inches) inside it. The double tank design functions to separate the seawater (outer) side from the mixing chamber region within the inner tank as well as to control the water flow between the two regions. The flow control plates allow for easy modification to the location and volume of water entering the inner tank.

A series of mixing chamber tests were conducted using a prototype mixing chamber. The initial tests were to verify the concept of the mixing chamber. The subsequent tests were to investigate modifications to the mixing chamber and to test different types of feed pumps.

The first test demonstrated that water levels were as designed and the water flow behaved as intended. To minimize feed pellet damage, a fish pump was selected for testing. A fish pump is typically a centrifugal pump with a modified impeller to allow pumping of large solids that operates at a lower revolution rate (less than 100 revolutions per minute).

Subsequent tests were performed using the fish pump with the addition of feed into the system. The feed exited the mixing chamber quickly, passes through the feed pump and was discharged into a water reservoir and caught in a net basket. The feed pumped through the system smoothly with minimal damaged feed. This confirmed the decision that a fish pump was necessary for the final feeding system design.

III. PHYSICAL MODEL

To investigate wave response, a physical scale model was constructed (Fig. 6). The scale model factor was determined by using a depth-based approach. The ratio of the depth of water at the expected buoy location over the depth of the UNH wave/tow tank was used resulting in a Froude scale factor of 1:20.7. The resulting physical scale model was 16.125 inches tall (not including mast), 13 inches in diameter and weighed 19.6 pounds (load condition) or 15.2 pounds (light condition).

Free-release and wave tests were conducted at UNH in the

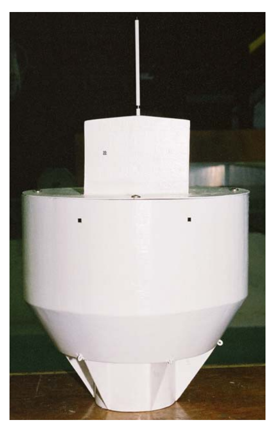

Figure 6. Completed 1:20.7 buoy scale model.

Ocean Engineering wave/tow tank. A total of 10 different regular wave inputs were tested. Wave periods/frequencies bracketed common wind generated, storm and sea swell waves found at the expected location for the buoy (see Table 1). For the wave tests a Froude scaled mooring was created and consisted of a long length of line (540 inches), including a one foot elastic section, connected to a short section of chain (52 inches) that was attached to a bottom anchor. The wave tests were conducted using a worst case mooring scenario that consisted of only one mooring leg. All tests were performed under two different loading conditions: load and light. The load case corresponds to a buoy with full feed and fuel, while the light case is strictly permanent structures on the buoy.

The data for both the heave and pitch tests were acquired using UNH's optical positioning instrumentation and evaluation (OPIE) measurement system, described in [11]. The OPIE system uses a digital camera, computer and processing software to track the motion of black dots placed on the white buoy. The data exported by OPIE was then further analyzed using Matlab® software. For each type of test and loading, a set of at least six tests were recorded.

From the free-release tests the damped natural period (Td) values were determined for both heave and pitch and scaled to full scale buoy values. The heave/pitch Td values were found to be 3.41/4.64 seconds and 3.65/4.83 seconds for the light and load case respectively.

The wave testing resulted in values for the Heave, Surge, and Pitch Response Amplitude Operators (RAOs). The RAOs are defined as the ratio of the buoy response amplitude to the wave forcing amplitude. Heave, Surge, and Pitch RAOs were calculated, and the results plotted as a function of frequency in Fig. 7a-c.

The buoy will follow the wave vertical motion at lower frequencies, as can be seen in the Heave RAO plot (Fig. 7a). The Heave natural frequency of 0.2835 Hertz (average value) is visible in the Heave RAO plot. In higher frequency waves, the buoy has Heave RAO values less than 1.2, so motion will not be excessive. In the frequencies when the buoy has a large

TABLE 1
Regular wave input parameters. Subscript fs indicates full scale. T is period; H is wave height; f is frequency, and λ is wavelength.

	Inputs$_{fs}$				
#	T_{fs} (sec)	H_{fs} (m)	f_{fs} (Hz)	λ_{fs} (m)	Steepness^-1 (λ/H)
1	2.28	0.54	0.439	8.1	15.0
2	2.96	0.91	0.338	13.7	15.0
3	3.64	1.39	0.274	20.7	14.9
4	4.33	1.95	0.231	29.2	15.0
5	5.33	2.97	0.188	44.3	14.9
6	6.83	4.85	0.146	72.8	15.0
7	8.79	5.60	0.114	119.9	21.4
8	10.02	4.77	0.100	154.0	32.3
9	11.98	3.53	0.083	211.2	59.9
10	13.66	2.28	0.073	260.1	114.0

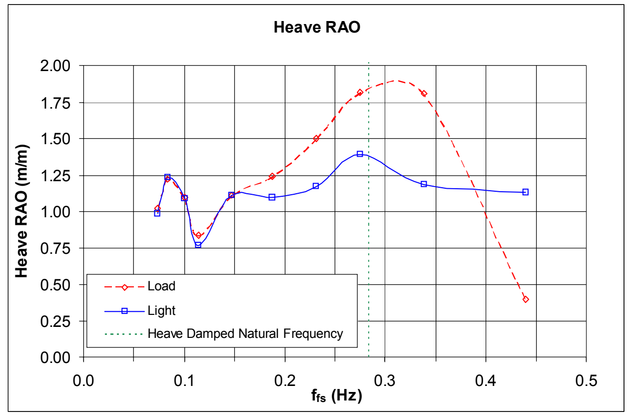

Figure 7a. Heave RAO for load and light case. Heave RAO is heave amplitude normalized by wave amplitude.

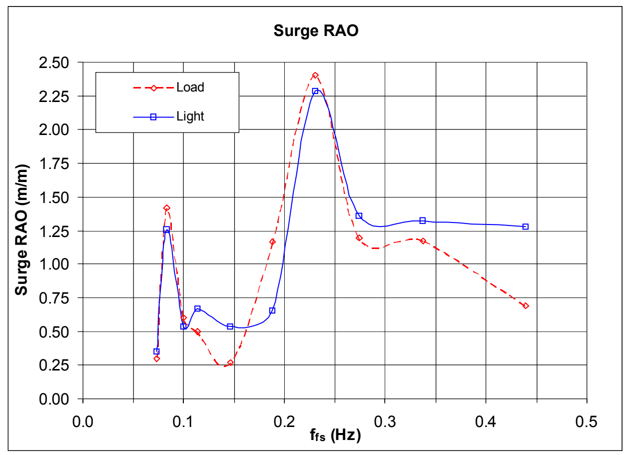

Figure 7b. Surge RAO for load and light case. Surge RAO is buoy horizontal amplitude normalized by fluid particle horizontal amplitude at the mean surface.

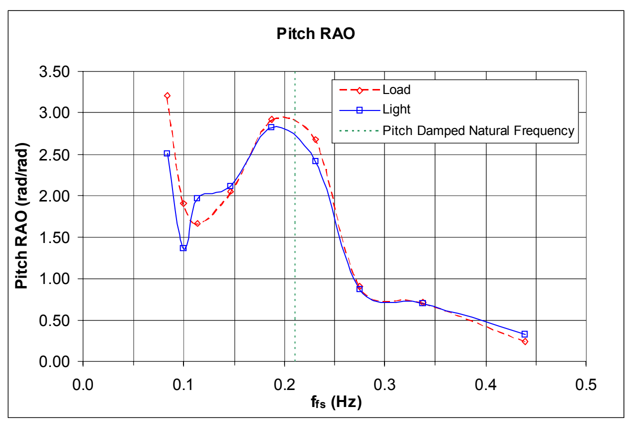

Figure 7c. Pitch RAO for load and light case. Pitch RAO is buoy pitch amplitude (in radians) normalized by maximum wave slope ($\frac{2\pi}{\lambda}\frac{H}{2}$).

Heave RAO (greater than 1.5) the energy present in the waves is manageable. The Heave RAO plot (all conditions) also matches up with the damped natural frequency determined in previous heave free-release tests.

The Surge RAO plot (Fig. 7b) shows two peaks at 0.083 Hertz and 0.231 Hertz, with greater values at the higher wave frequency peak. At higher wave frequencies the Surge RAO values are close to unity.

From the Pitch RAO plot (Fig. 7c), two peaks in RAO values are visible. One peak is the result of the Pitch natural period of 4.74 seconds (average value), frequency of 0.2112 Hertz, with Pitch RAO values greater than 2.5 and is also visible in the Surge RAO plot. The lower frequency value, 0.083 Hertz, is a result of the mooring system coupled with the buoy's surge motion and is also visible in the Surge RAO plot.

Based upon the model tests, the buoy is a wave follower with respect to vertical motion and should not have very severe reactions to wave spectra that are normally observed at the Isles of Shoals site.

Due to the pitch response activity over the lower frequency test range a second series of wave tests were completed using a higher mooring attachment location. This test was to determine if the higher mooring attachment location, closer to the center of gravity of the buoy, would result in lower Pitch RAO values. The tests were conducted over the same range of wave profile inputs as that of the original tests and were analyzed using the same procedures. The changes in the RAO values for the different mooring attachment points did not justify the significant design changes that would have arisen from moving the mooring attachment points. The mooring attachment location points on the buoy remain at the original, lower attachment point.

IV. AQUA-FE COMPUTER MODELING

To design the mooring system, a computer model was generated in Aqua-FE. Aqua-FE is a finite element analysis program that has the ability to investigate objects in a wave environment, and is being used to design the mooring system for the Isles of Shoals site [5]. Due to space limitations in the ocean engineering wave/tow tank at UNH, the full mooring system could not be set up for physical experiments. Aqua-FE was applied to the full system, including the cage and site grid, and was used to model the response to large amplitude storm waves combined with current. (Feed buoy representation parameters were optimized by applications to the scale model tank tests and comparing computer predictions with measurements.)

The current design for the feed buoy mooring is to use a four leg system separate from the UNH OOA grid system (Fig. 8). The feed buoy mooring was not incorporated into the grid system for two reasons: it was not designed to hold a large surface buoy, and the grid was to be maintained as an independent scientific/engineering platform. The northeast (NE) grid corner was chosen for the buoy location in order to minimize the distances from the buoy to the cages to keep feed hose lengths as short as possible as well as having the mooring legs that leave the site be parallel to the navigation LORAN lines. The buoy could not be located inside the grid due to the interference of the mooring with grid cage surfacing operations. A large scope (6:1) was desired for the mooring to minimize the downward force that would be exerted on the buoy with a tight mooring. Design work is progressing iteratively as mooring components are sourced, costs compared and installation procedures developed.

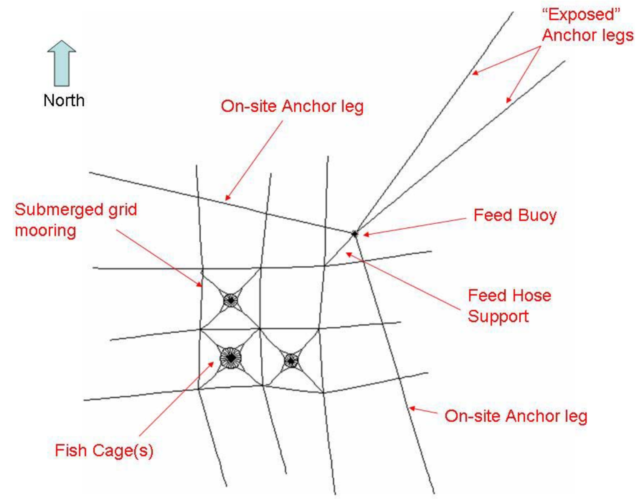

Figure 8. General layout of the UNH OOA submerged grid system (as deployed) with the current design of the 20-ton feed buoy mooring.

The Aqua-FE analyses were performed using multiple wave heights, periods, and currents. The majority of the analyses were done using UNH's design wave that has the following parameters: 9.0 meter wave height, 8.8 second period, and 1 meter per second current that is constant with depth and in the direction of the wave train. Using UNH's design wave and a worst-case scenario, one mooring leg taking the entire load of the wave forcing, the maximum tension that was found in a single anchor leg was 282 kilo-newtons. With the current mooring design the buoy's watch circle will be a maximum/minimum straight line distance of 72/49 meters from the NE grid corner. The expected operating distance of the buoy from the NE grid corner is 49 meters.

V. CONSTRUCTION

Aquaculture Engineering Group (AEG) was contracted to fabricate and deliver the buoy to UNH. Construction began in early March at AEG's fabrication facility located in Weldon, NB, Canada. The major buoy hull components are being fabricated in four separate modules: the machine house, the main deck, the main hull, and the ballast can. Once the modules are complete they are to be shipped to the launch site where final assembly will occur. All internal components are to be dry fit before transport to the launch site. At the time of writing the major buoy hull components were completed, but not yet assembled into a single hull.

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